15

Elementary Particles

15.1. Introduction

After studying the structure of atoms, one gets the impression that perhaps electron, proton and neutron are the only building blocks of matter. Recently the extensive studies made partly on high energy cosmic ray particles and even more, with the help of high energy accelerators, have revealed the existence of numerous new nuclear particles.

The subatomic or elementary particles discovered so far, form a long list (around 200). These particles are elementary in the sense that they are structureless, *i.e.*, they cannot be explained as a system of other elementary particles. Table 15.1 shows the elementary particles having relatively long life. Their classification is as follows :

(A) Baryons (or heavy particles). Proton and particles heavier than proton form this group. Proton and neutron are called *nucleons* and the rest are called *hyperons*. Every baryon has an *antiparticle*. If a number, called the baryon number +1 is assigned to baryons and a number -1 is assigned to antibaryons, then in any closed system interaction or decay, the baryon number does not change. This is the law of conservation of baryons.

Hyperons is a special class of baryons characterised by a time decay of the order of 10^{-10} seconds and mass value intermediate between those of the neutron and deuteron. Their decay time is very much greater than the time of their formation (10^{-3} sec). It is because of this unsolved problem, that these particles, along with the *K*-mesons, are called *strange particles*. There are four types of hyperons; Lambda, Sigma, Xi and Omega.

(B) Leptons. This group contains electron, photon, neutrino and muon.

(C) Mesons. The rest mass of these particles varies between about $250m_e$ and $1000m_e$. The mesons are the agents of interaction between particles inside the nucleus. Baryons and mesons, are jointly called *hadrons*.

and are the particles of strong interaction.

Table 15.1. Elementary particles

	Name	Symbol	Rest Energy M_0 /MeV	Mean lifetime τ/s	Common decay modes
Leptons	Photon	γ	0	stable	
	Neutrino	ν_e	0	stable	
		ν_μ	0	stable	
	Electron	$e^\pm$	0.511004(2)	stable	
	Muon	$\mu^\pm$	105.659(2)	$2.1994(6)\times10^{-6}$	$e\,\nu\,\bar{\nu}$
Mesons	Pion	$\pi^\pm$	139.576(11)	$2.602(2)\times10^{-8}$	$\mu\nu$
		π^0	134.972(12)	$0.84(10)\times10^{-16}$	$\gamma\gamma$ (99%)γe^+e^- (1%)
	Kaon	$K^\pm$	493.82(11)	$1.235(4)\times10^{-8}$	$\mu\nu$(64%)$\pi^+\pi^0$(21%) 3π(5%)
		K^0	497.76 (16)	50% K_1, 50% K_2	
		K_1		$8.62\ (6)\times10^{-11}$	$\pi^+\pi^-$(69%)$2\pi^0$(31%)
		K_2		$5.38\ (19)\times10^{-8}$	$\pi e\,\gamma$(39%)$\pi\mu\nu$(27%) $3\pi^0$(21%)$\pi^+\pi^-\pi^0$(13%) $\gamma\gamma$(38%)$\pi\gamma\gamma$(2%)$3\pi^0$ (31%)$\pi^+\pi^-\pi^0$(23%) $\pi^+\pi^-\gamma$(5%)
	Eta	η^0	548.8(6)		
Baryons	Proton	$p^\pm$	938.256(5)	Stable	
	Neutron	n	939.550(5)	$9.32(14)\times10^{2}$	pev
	Lambda	Λ^0	1115.60(8)	$2.51(3)\times10^{-10}$	$p\pi^-$ (65%)$n\pi^0$ (35%
	Sigma	Σ^+	1189.4(2)	$8.02(7)\times10^{-11}$	$p\pi^0$(52%)$n\pi^+$(48%)
		Σ^0	1192.46(12)	$<10^{-14}$	$\Lambda\gamma$
		Σ^-	1197.32(11)	1.49×10^{-10}	$n\pi^-$
	Xi	Ξ^0	1314.7(7)	$3.03(18)\times10^{-10}$	$\Lambda\pi^0$
		Ξ^-	1321.25(18)	$1.66\ (4)\times10^{-10}$	$\Lambda\pi^-$
	Omega	Ω^-	1672.5(5)	$1.3(4)\times10^{-10}$	$\Xi^0\pi^-$, $\Xi^-\pi^0$, ΛK^-(?)

15.2. Particles and Anti-particles

Electron and Positron. The positron and the electron are said to be antiparticles. They have the same mass and the same spin but opposite charge. They annihilate each other with the emission of photons, when they come in contact with each other. The existence of an antiparticle for the electron was actually predicted by Dirac, because of a symmetry of the equations of the relativistic quantum theory of the electron. Positron was discovered by Anderson in 1932.

Proton and antiproton. Dirac's theory, anticipating the positron, could be interpreted as implying a particle identical to the proton except for a negative charge. The existence of this particle, the *antiproton*, was established in 1955 by Segre, Chamberlain, and their collaborators. Antiprotons were produced by bombarding protons in a target

with 6-GeV protons, thereby inducing the reaction

$$p + p\,(+\text{energy}) \rightarrow p + p + p + p$$

The K.E. of the bombarding proton is converted to a proton-antiproton pair plus the K.E. of the four residual particles. Antiprotons interact strongly with matter and annihilate with protons. In a typical annihilation reaction the rest mass of the annihilating pair appears as five pions and their K.E.

$$p + \bar{p} \rightarrow \pi^+ + \pi^- + \pi^+ + \pi^- + \pi^0.$$

Neutron and antineutron. The antiparticle of neutron, *antineutron*, was discovered in 1956 by Cork, Lamberton and Wenzel. The nature of the antineutron is not very well known. Both neutron and antineutron have zero charge and the same mass. However, since neutron is supposed to have a certain internal charge distribution, it is expected that the antineutron has an internal charge distribution opposite to that of the neutron. Antineutron is quickly annihilated, either by a proton or a neutron, usually with the production of several pions. If an antineutron is not annihilated by a nucleon, it decays by the reaction

$$\bar{n} \rightarrow \bar{p} + \beta^+ + \nu$$

Neutrino and antineutrino. As discussed in chapter 11, it is possible to avoid violations of the law of conservation of energy, linear and angular momenta and spin by assuming the existence of a particle, called a *neutrino*. It has *charge zero, spin 1/2, zero rest mass (rest mass very small in comparison with that of the electron) and magnetic moment smaller than 10^{-8} Bohr magneton or nearly zero*. The neutrino has a finite energy and momentum in flight. It travels with the speed of light c. It does not cause ionization on passing through matter.

The antiparticle of neutrino is *antineutrino*. The distinction between the neutrino ν and antineutrino $\bar{\nu}$ is a particularly interesting one. The spin of the neutrino is opposite in direction to the direction of its motion; viewed from behind, the neutrino spins counterclockwise. But the spin of the antineutrino is in the same direction as its direction of motion; viewed from behind, it spins clockwise. Thus the neutrino moves through space in the manner of a left-handed screw, while the antineutrino does so in the manner of a right-handed screw. Thus a neutrino possesses a "left-handed" helicity; the antineutrino possesses a "right-handed" helicity, *i.e., a neutrino and antineutrino differ only in the sense of their helicity*.

It is customary to call the particle accompanying a positron a neutrino, ν, while that accompanying an electron is called an antineutrino, $\bar{\nu}$. It is important to remember that positrons and electrons are never ejected alone. It is clear from experiments that neutrinos emitted in β decay (positron decay and K-capture) have a negative helicity, *i.e.*, they are longitudinally polarized with their spin axes antiparallel to their direction of travel.

$$\mathbf{H} = +1 \text{ for } \bar{\nu}\,; \quad \mathbf{H} = -1 \text{ for } \nu$$

Because of its lack of charge and magnetic moment, a neutrino has essentially no interaction with matter, except that which leads to inverse β decay. This interaction is extremely weak. The cross section for this process is only $\sigma \approx 10^{-48}\ m^2 \approx 10^{-20}$ *barn*. Matter is almost totally transparent to neutrinos.

15.3. Antimatter

In Atomic Physics, it has long been useful to consider an atom as composed of extranuclear electrons and a nucleus formed of protons and neutrons. There is reason to believe that a *positron* and an *antiproton* could form an atom of *antihydrogen*. Antihydrogen would have a spectrum similar to that of ordinary hydrogen. Indeed, from a collection of antiprotons, antineutrons, and positrons, a world of antimatter might be constructed, which could be indistinguishable from our world so long as everything were made of antiparticles. However, if some of this *contraterrene* matter were to come in contact with the ordinary matter, particle-antiparticle annihilation would occur with a tremendous release of energy.

15.4. The Fundamental Interactions

Four kinds of interaction between elementary particles can account for all known processes in the physical universe on all scales of size. In Table 15.2 the four basic interactions are summarised.

Table 15.2. The Four Fundamental Interactions

Interaction	Particles Affected	Range	Relative Strength	Particles Exchanged
Strong	Hadrons	$\sim 10^{-15}$ m	1	Mesons
Electro-magnetic	Charged Particles	∞	$\sim 10^{-2}$	Photons
Weak	Hadrons and leptons	$\sim 10^{-17}$ m	$\sim 10^{-13}$	Intermediate bosons
Gravitational	All	∞	$\sim 10^{-40}$	Gravitons

(1) Strong interaction. A familiar example of strong interaction is the forces which hold nucleons together (nuclear forces) in the atomic nucleus. The strong nuclear interaction is independent of the electric charge. The

range of these interactions is about 10^{-15} m. Time interval of such an interaction is roughly 10^{-23}s.

(2) **Electromagnetic interaction.** It operates on all charged particles. Thus electromagnetic interactions are charge dependent (attractive as well as repulsive). The range is infinite and the interaction works through the *photon*. The formation of electron-positron pair from γ-ray is an example of electromagnetic interaction.

(3) **Weak interaction.** All strong interactions take place in times of about 10^{-23} s (characteristic time). Yet is has been observed that some of the resulting particles, although energetically unstable, suffer no decay until a time 10^{13} times greater than 10^{-23} is reached. That is, their decay takes place in time of about 10^{-10} s. For example, β-decay of radioactive nuclei does not take place until a time 10^{13} times greater than that involved in strong interactions has approached. Had there been strong nuclear or electromagnetic interactions, there would have been no such delay in the decay process. Therefore, this delay in the decay process suggests that either these particles are not subjected to strong interacting forces or there is some new conservation law or prohibition which forbids the decay. But since most of the particles involved are subjected to either nuclear force or have electric charge or both, there must be some rule which stops the process. But eventually the decays do happen, there must be some other type of interaction as predicted by Fermi to explain β-decay. Since particles take long time to respond to such an interaction, force involved must be very weak compared with strong nuclear forces. The range of such an interaction is less than 10^{-17}m. The characteristic time of this interaction is $\approx 10^{-10}$s. Yukawa, in 1938, suggested that there should be a field quantum for the weak interaction, corresponding to the photon and pion. This so called *'intermediate vector boson'* has not been experimentally detected as a free particle. The weak interaction is responsible for the decay of strange and non-strange particles and for non-leptonic decays of strange particles.

(4) **Gravitational interaction.** It is the weakest of the four types of interactions. It has infinite range. Although gravity has a measurable influence on macroscopic bodies, its interaction with subnuclear particles is very small. Gravitation can be explained in terms of the interactions of *'gravitons'*. Their mass must be zero, and therefore, their velocity must be that of light. As the gravitational field is extremely weak, the gravitons cannot be detected in the laboratory.

Of the four basic forces, only gravitational force is universal. Weak forces affect every particle other than photon. Electromagnetic force is confined to charged particles. Strong forces are the most selective and they serve as the criteria for classifying all known particles other than photons into two broad categories, the *leptons* and the *hadrons*. Leptons and photons

are light particles and do not feel the strong forces. But hadrons feel the strong forces and participate in strong interactions besides taking part in other types of interactions as well. Thus the proton is a strongly interacting nuclear constituent and is therefore, a hadron. At the same time, because of its charge and mass, it must also experience electromagnetic and gravitational forces. The fact that it can be created by β-decay of neutron shows that the proton is involved in weak interactions as well.

15.5. Elementary-particle quantum numbers

In classifying the various elementary particles, several discrete quantum numbers are used. We are already familiar with two such quantum numbers, namely those that describe a particle's *charge* and *spin*. These quantum numbers specify measurable physical properties and are always conserved. We know that all elementary charges are 0 or ± 1. The charge is conserved in all processes and no exceptions are known. The spin quantum number J is either an integer or an half odd integer for the particles so far detected. Particles with integer spin obey the Bose-Einstein statistics and are called *bosons*. Particles with half odd integer spins obey the Fermi-Dirac statistics and are called *fermions*. The other quantum numbers are more abstract and it is not always clear precisely to what aspect of physical reality they refer.

(a) **Baryon number.** Each baryon is given a baryon number $B=1$, each corresponding antibaryon is given a baryon number $B=-1$. All other particles have $B=0$. The law of conservation of baryons states that the sum of the baryon numbers of all the particles after a reaction or decay must be the same as their sum before. This rule ensures that a proton cannot change into an electron, even though a neutron can change into a proton. Baryon conservation ensures the stability of the proton against decaying into a particle of smaller mass.

(b) **Lepton number.** Leptons are supposed to possess a property called *Lepton number (L)*. Since the neutrinos associated with electrons and with muons are recognised as different, we introduce two lepton numbers L_e and L_μ, both of which must be conserved separately in particle reactions and decays. The number $L_e=1$ is assigned to the electron and the e-neutrino and $L_e=-1$ to their antiparticles. All other particles have $L_e=0$. Also, the number $L_\mu=1$ is assigned to the muon and the μ-neutrino and $L_\mu=-1$ to their antiparticles. All other particles have $L_\mu=0$. An example of particle-number conservation is the decay of the neutron, in which $B=1$ and $L_e=0$ before and after :

$$\begin{aligned} n &\rightarrow p + e^- + \bar{\nu}_e \\ B: +1 &\rightarrow (+1) + 0 + 0 \\ L_e: 0 &\rightarrow 0 + (+1) + (-1) \end{aligned}$$

This is the only way in which the neutron can decay and still conserve

both energy and baryon number B. Similarly, pion decay illustrates the conservation of L_μ :

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$L_\mu : 0 \rightarrow (+1) + (-1)$$

(c) **Strangeness number.** The properties of K-mesons and hyperons appeared at first instance to be paradoxical in that they were produced by high energy reactions but always in pairs *i.e.*, if one particle of some kind is produced then simultaneously another different particle is also emitted. This is termed as the *associated production* of kaons and hyperons which are known as *strange particles*. Furthermore as they are produced in strong interaction, one should expect them to decay also through strong interactions in a very short time but this is not observed. Instead they decay slowly. Because of this strange behaviour they were called as strange particles. Their production is typical of strong interaction such as :

Table 15.3

Class	Name	Symbol	Spin	B	Le	L_μ	S	Y	I
LEPTON	e-neutrino	ν_e	$\frac{1}{2}$	0	+1	0			
	μ-neutrino	ν_μ	$\frac{1}{2}$	0	0	+1			
	Electron	e^-	$\frac{1}{2}$	0	+1	0			
	Muon	μ^-	$\frac{1}{2}$	0	0	+1			
MESON	Pion	π^+ π^0 π^-	0	0	0	0	0	0	1
	Kaon	K^+ K^0	0	0	0	0	+1	+1	$\frac{1}{2}$
	η meson	η^0	0	0	0	0	0	0	0
BARYON	Nucleon (Proton Neutron)	p n	$\frac{1}{2}$	+1	0	0	0	+1	$\frac{1}{2}$
	Λ hyperon	Λ^0	$\frac{1}{2}$	+1	0	0	−1	0	0
	Σ hyperon	Σ^+ Σ^0 Σ^-	$\frac{1}{2}$	+1	0	0	−1	0	1
	Ξ hyperon	Ξ^0 Ξ^-	$\frac{1}{2}$	+1	0	0	−2	−1	$\frac{1}{2}$
	Ω hyperon	Ω^-	$\frac{3}{2}$	+1	0	0	−3	−2	0

lementary

$$\pi^- + p^+ \rightarrow \wedge^\circ + K^\circ$$

and their decay

$$\wedge^\circ \rightarrow p + \pi^-$$

$$K^\circ \rightarrow \pi^+ + \pi^-$$

s through weak interaction.

This and other considerations led to the notion of *strangeness number* S. $S=0$ for the nucleons, and $S\neq 0$ for kaons and hyperons (Table 15.3). It is found that S is conserved in all processes mediated by the strong and electromagnetic interactions. Kaons and hyperons, which have $S\neq 0$, are created in high-energy collisions that involve the strong interaction. Their multiple appearance results from the necessity to conserve S. An example is the proton-proton collision :

$$p^+ + p^+ \rightarrow \wedge^\circ + K^\circ + p^+ + \pi^+$$

$$S: 0 + 0 \rightarrow (-1) + 1 + 0 + 0$$

On the other hand, S can change in an event governed by the weak interaction. The decays of kaons and hyperons proceed via the weak interaction and accordingly are extremely slow. Even the weak interaction, however, is unable to permit S to change by more than ± 1 in a decay.

(d) **Hypercharge.** A quantity called *hypercharge* (Y) is conserved in strong interaction. Hypercharge is equal to the sum of the strangeness and baryon numbers of the particle families : $Y=S+B$. The various hypercharge assignments are listed in Table 15.3.

(e) **Isospin and Isospin quantum number.** As far as strong interactions are concerned, the neutron and the proton are two states of equal mass of a nucleon doublet. From Table 15.1, it is found that particles occur in multiplets. For example, singlets η°, Ω^-, $\wedge^\circ$. Doublet: p,n, triplet π°, π^-, π^+ . It is natural to think of the members of a multiplet as representing different charge states of a single fundamental entity. It has proved useful to categorize each multiplet according to the number of charge states it exhibits by a number I such that the multiplicity of the state is given by $2I+1$. Thus the nucleon multiplet is assigned $I=1/2$, and its $2\times 1/2+1=2$ states are the neutron and the proton. The pion multiplet has $I=1$, and its $2\times 1+1=3$ states are π^+, π° and π^-.

Isospin can be represented by a vector I in "isospin space" whose component in any specified direction is governed by a quantum number customarily denoted I_3. The possible values of I_3 are restricted to I, $I-1$, $I-2$....., 0, ... $-(I-1)$, $-I$. Hence I_3 is half-integral if I is half-integral and integral or zero if I is integral. For the nucleon, $I=1/2$ and $I_3=1/2$ corresponds to the proton, $I_3=-1/2$ for the neutron. Similarly, for the pion triplet $I=1$ giving $I_3=+1$ for π^+, 0 for π and -1 for π^-. The charge of a meson or baryon is related to its baryon number B, its strangeness number S, and the component I_3 of its isospin by the formula

$$q = e\left(I_3 + \frac{B+S}{2}\right) = e\left(I_3 + \frac{Y}{2}\right)$$

15.6. Conservation Laws and Symmetry

A very important set of conservation laws is related to symmetries involving parity (P), charge conjugation (C), and time reversal (T).

Conservation of parity. Parity relates to the symmetry of the wave function that represents the system. If the wave function is unchanged, when the coordinates (x, y, z) are replaced by $(-x, -y, -z)$, then the system has a parity of +1. If the wave function has its sign changed, when the coordinates are reversed, then the system has a parity of -1. If we write $\psi(x,y,z) = P\psi(-x, -y, -z)$, we can regard P as a quantum number characterizing ψ whose possible values are +1 and −1. During a reaction in which parity is conserved, the total parity number does not change.

Changing the coordinates (x,y,z) into $(-x, -y, -z)$ converts a right-handed coordinate system into a left-handed coordinate system. In terms of symmetry, the meaning of conservation of parity is that in any situation where parity is conserved, the description of the reaction will not be changed if the word "left" is changed to the word "right" and vice versa. This means that such reactions can provide no clue that will distinguish between the directions right and left. Prior to 1956 it was believed that all reactions in nature obeyed the law of conservation of parity. However, Yang and Lee pointed out that in reactions involving the weak interaction, parity was not conserved, and that experiments could be devised that would absolutely distinguish between right and left. Indeed parity conservation is found to hold true only in the strong and electromagnetic interactions.

Charge conjugation symmetry. Charge conjugation is the act of symmetry operation in which every particle in a system is replaced by its antiparticle. If the anti-system, or antimatter counterpart exhibits the same physical phenomena, then charge parity (C) is conserved. For example, if in a hydrogen atom, the proton is replaced by an antiproton and the electron is replaced by a positron, then this antimatter atom will behave exactly like an ordinary atom, if observed by people also made of antimatter. In fact C is not conserved in the weak interaction.

Time reversal symmetry. Time parity T describes the behaviour of a wave function when t is replaced by $-t$. The symmetry operation that corresponds to the conservation of time parity is time reversal. Time reversal symmetry implies that the direction of time is not significant, so that the reverse of any process that can occur is also a process that can occur. In other words, if symmetry under time reversal holds, it is impossible to establish by viewing it whether a motion picture of an event is being run forward or backward. Prior to 1964, time parity T was considered to be conserved in every interaction. It was discovered in 1964 that one form of the K^0 kaon

can decay into $\pi^+ + \pi^-$, which violates the conservation of T. The symmetry of phenomena under time reversal thus does not seem to be universal.

Combined Inversion of CPT. The combined symmetry operation in which the antimatter mirror-image of a system is run in reverse allows a test of CPT invariance. All the evidence supports the conservation of CPT. The conservation of CPT means that for every process there is an antimatter mirror-image counterpart that takes place in reverse. This particular symmetry seems to hold for all interactions, even though its component symmetries sometimes fail individually.

15.7. The Quark Model

Murray Gell-Mann and G. Zweig proposed the quark model in 1964. This theory is based on the idea that the hadrons are built up from a limited number of "fundamental" units, which have acquired the name quarks. The original three quarks were labeled u (for "*up*"), d (for "*down*") and s (for "*strange*").

u quark has electric charge $+\frac{2}{3}e$ and strangeness 0.

d quark has electric charge $-\frac{1}{3}e$ and strangeness 0.

s quark has electric charge $-\frac{1}{3}e$ and strangeness -1.

Each quark has a baryon number of B=1/3.

Each quark has an antiquark associated with it ($\bar{u}$, $\bar{d}$, and $\bar{s}$). In magnitude of each of the quantum numbers for the antiquarks has the same magnitude as those for the quarks, but the sign is changed.

Compositions of hadrons according to the quark model.

Hadrons may be *baryons* or *mesons*. A baryon is made up of three quarks. For example, the proton is made up of two u quarks and a d quark (uud). For these quarks, the electric charges are +2/3, +2/3, and -1/3 for a total value of +1. The baryon numbers are +1/3, +1/3 and +1/3, for a total of +1. The strangeness numbers are 0, 0 and 0 for a total strangeness of 0. All are in agreement with the quantum numbers for the proton. Fig. 15-1 shows quark models of the proton, antiproton, neutron, and antineutron. Electric charges are given in units of e.

A meson is made up of one quark and one antiquark. For example, the π^+ meson is the combination of a u quark and a $\bar{d}$ antiquark ($u\bar{d}$). Electric charges of these quarks are +2/3 and +1/3 for a total of +1. The baryon numbers are +1/3 and -1/3 for a total baryon number of 0. The strangeness numbers are 0 and 0 for a total of 0. All of these are in agreement with the quantum numbers for the pi-meson. Quarks all have spins of 1/2, which accounts for the observed half integral spins of baryons and the 0 or 1 spins of mesons.

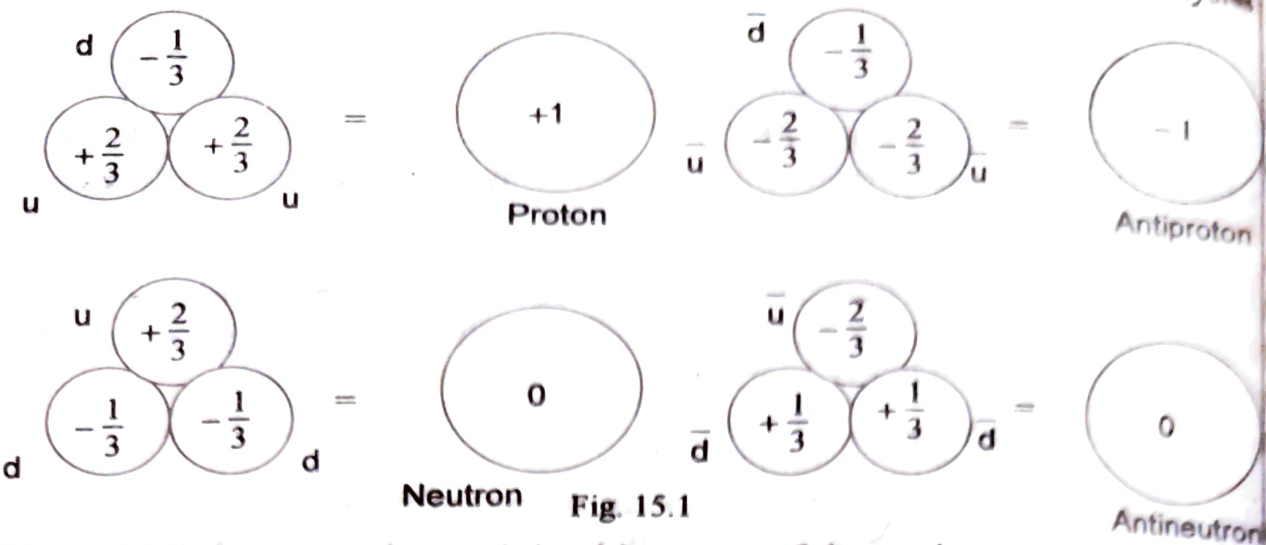

Fig. 15.1

All known hadrons can be explained in terms of the various quarks and their antiquarks. Table 15-4 shows the quark contents of five hadrons and how they account for the observed charges, spins, and strangeness numbers of these particles.

Coloured quarks and gluons : There were problems with the quark model, one of them being Ω^- hyperon. It was believed to contain three identical *s* quarks. (*sss*). This violates the Pauli exclusion principle, that prohibits cha-

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Table 15.4 Compositions of Some Hadrons According to the Quark Model

	Quark content	Baryon number	Charge, e	Spin	Strangeness
	$u\bar{d}$	$\frac{1}{3}-\frac{1}{3}=0$	$+\frac{2}{3}+\frac{1}{3}=+1$	$\uparrow\downarrow=0$	$0+0=0$
K^+	$u\bar{s}$	$\frac{1}{3}-\frac{1}{3}=0$	$+\frac{2}{3}+\frac{1}{3}=+1$	$\uparrow\downarrow=0$	$0+1=+1$
p^+	uud	$\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=+1$	$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$	$\uparrow\uparrow\downarrow=\frac{1}{2}$	$0+0+0=0$
n^0	ddu	$\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=+1$	$-\frac{1}{3}+\frac{1}{3}+\frac{2}{3}=0$	$\downarrow\downarrow\uparrow=\frac{1}{2}$	$0+0+0=0$
Ω^-	sss	$\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=+1$	$-\frac{1}{3}-\frac{1}{3}-\frac{1}{3}=-1$	$\uparrow\uparrow\uparrow=\frac{3}{2}$	$-1-1-1=-3$

two or more ferminons from occupying identical quantum states. The proton, neutron, and others with two identical quarks would violate this principle also. We can resolve this difficulty by assigning a new property to the quarks. We can regard this new property as an additional quantum number that can be used to label the three otherwise identical quarks in the Ω^-. If this additional quantum number can take any one of three possible values, we can restore the Pauli principle by giving each quark a different value of this new quantum number, which is known as *colour*. The three colours are labeled red (*R*), blue (*B*), and green (*G*). The Ω^- for example, would then $s_R\, s_B\, s_G$. The antiquark colours are antired ($\bar{R}$) antibule ($\bar{B}$) and antigreen ($\bar{G}$).

An essential component of the quark model with colour is that *all observed meson and baryon states are "colourless"*, i.e., either colour anticolour combinations in the case of mesons, or equal mixtures of *R*, *B* and *G* in the case of baryons.

Since hadrons seem to be composed of quarks, the strong interaction between hadrons should ultimately be traceable to an interaction between quarks. The force between quarks can be modeled as an exchange force, mediated by the exchange of massless spin-1 particles called gluons. Eight gluons have been postulated. The field that binds the quarks is a *colour field*. *Colour is to the strong interaction between quarks as electric charge is to the electromagnetic interaction between electrons.* It is the fundamental strong "charge" and is carried by the gluons. The gluons must therefore be represented as combinations of a colour and a possibly different anticolour. The gluons are massless and carry their colour-anticolour properties just as other particles may carry electric charge. For example, Fig. 15-2 shows a gluon $R\bar{B}$ being exchanged by red and blue quarks. In effect the red quark emits its redness into a gluon and acquires blueness by also emitting antiblueness. The blue quark, on the other hand, absorbs the $R\bar{B}$ gluon, canceling its blueness and acquiring a red colour in the process.

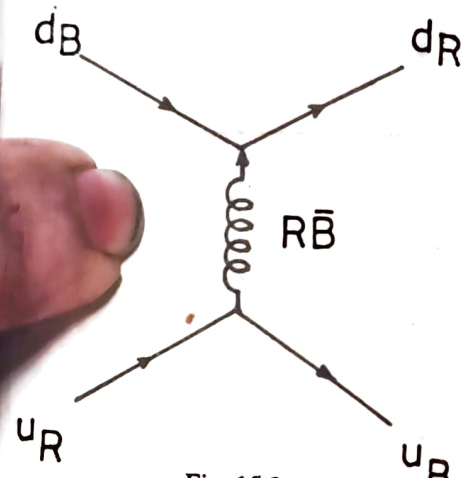

Fig. 15.2

Charm, Bottom, and Top. In 1970, Glashow, Iliopoulis, and Maiani proposed the existence of a fourth quark, called *c* or *charmed quark*. The charmed quark was suggested to explain the suppression of certain decay processes that are not observed. With only three quarks, the processes would proceed at measurable rates and should have been observed. The charm quark has a charge of $\frac{2}{3}e$, strangeness 0 and a charm quantum number of +1. Other quarks have 0 charm.

In 1977, a new particle was discovered at Fermi Lab that provided evidence for yet another quark. This particle, called the upsilon-meson, was thought to be made up of the new quark called *b* (for bottom or beauty) along with the associated antiquark $\bar{b}$. *b* quark has electric charge $-1/3e$.

Because quarks seem to come in pairs, it is expected that there is a partner to the *b* quark, called *t* (for top, if *b*=bottom, or truth, if *b*=beauty). It has a charge of $+2/3e$.

Three generations of quarks and leptons. Both leptons and quarks appear to come in three generations of doublets, with all particles having spin 1/2. Table 15.5 shows the properties of the three generations of quarks

and leptons. The first generation contains two leptons, the electron and the electron neutrino, and two quarks, up and down. All the properties of ordinary matter can be understood on the basis of these particles. The second generation includes the muon and muon-neutrino and the charm and strange quarks. These particles are responsible for most of the unstable particles and resonances created in high energy collisions. The third generation includes the tau and the tau-neutrino and the top and bottom quarks.

Table 15.5. Properties of the Three Generations of Quarks and Leptons

Generation	Quark	Symbol	Charge, e	Strangeness	Charm
1	Up	u	$+\frac{2}{3}$	0	0
	Down	d	$-\frac{1}{3}$	0	0
2	Charm	c	$+\frac{2}{3}$	0	+1
	Strange	s	$-\frac{1}{3}$	−1	0
3	Top	t	$+\frac{2}{3}$	0	0
	bottom	b	$-\frac{1}{3}$	0	0

Generation	Lepton	Symbol	Charge, e
1	Electron	e^-	−1
	e-Neutrino	ν_e	0
2	Muon	μ^-	−1
	μ-Neutrino	ν_μ	0
3	Tau	τ^-	−1
	τ-Neutrino	ν_τ	0

Exercise XV

1. Write short notes on *(a)* Elementary particles *(b)* Conservation laws in elementary particles *(c)* Weak nuclear interactions *(d)* Strange particles.

2. Which of the following reactions can occur? State the conservation laws violated by the others.

   (a) $p + p \rightarrow n + p + \pi^+$

   (b) $p + p \rightarrow p + \Lambda^0 + \Sigma^+$

   (c) $e^+ + e^+ \rightarrow \mu^+ + \pi^-$

   (d) $\Lambda^0 \rightarrow \pi^+ + \pi^-$

   (e) $\pi^- + p \rightarrow n + \pi^0$

   [Ans. *(a)* and *(e)* can occur; *(b)* does not conserve *B* or spin ; *(c)* does not conserve L_e, L_μ or spin ; *(d)* does not conserve *B* or spin.]

3. If the pion decays from rest to give a muon of 4.05 MeV energy, what is the K.E. of the accompanying neutrino? What is the mass of the neutrino in this process?

MODERN PHYSICS

(FOR B.Sc. PHYSICS STUDENTS OF ALL INDIAN UNIVERSITIES)

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